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DESIGN OF AN ELECTRONICALLY TUNABLE MILLIMETER WAVE GYROTRON BACKWARD WAVE OSCILLATOR

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ABSTRACT

A non-linear self-consistent computer simulation code is used to analyze the saturated output of the Gyrotron Backward Wave Oscillator (Gyro BWO) which can be used as a tunable driver for a 250 GHz FEL amplifier. Simulations show that the Gyrotron BWO using a Pierce/Wiggler gun configuration can produce at least 10 kW of microwave power over the range 249 GHz to 265 GHZ by varying beam voltage alone.

INTRODUCTION

There is a requirement for a low duty (~ 1%) tunable source near 250 GHz to serve as a driver for a 8 GW peak power FEL amplifier. The source is to be electronically tunable over millisecond time scales by ±3% with output powers of at least 10 kW ($\leq$ 3 dB power variation). The requirements for such a source can be met by a Gyrotron Backward Wave Oscillator. Figure 1 illustrates the basic physics of the device, namely the feedback between a backward TE waveguide mode and a forward cyclotron wave generated on the beam. The operating frequency occurs at the intersection points f_1 or f_2. Tuning can be achieved by varying the cyclotron frequency (ω intercept) or axial beam velocity (slope of the beam line).

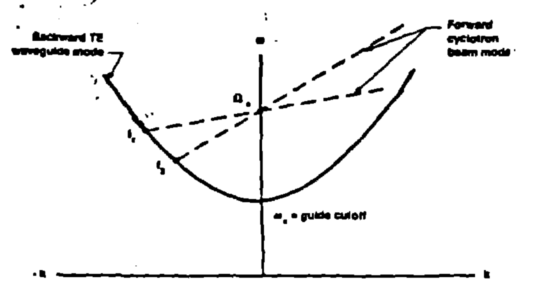

Fig. 1 Interaction Mechanism of the Gyrotron BWO

A minimum interaction length is required to excite the backward wave oscillation. This critical length as well as an approximate expression for the BWO mode structure can be obtained from linear gyrotron theory using methods analogous to those in analyzing helix tube BWO's.(1) The axial electric field profile and critical length L_c are given as:

$$|E(z)| = \cos(\pi z/2L_c)$$

$$L_c/\lambda_0 = 65\left(\frac{\lambda_c}{\lambda_0}\right)^2 \sqrt{\frac{\gamma\beta_z(1-\lambda_0^2/\lambda_c^2)[(\delta v_z/v_z)+(\Delta/k_z v_z)]}{I_B\alpha^2 G}}$$

where λ_c = cutoff wavelength
λ_0 = free space wavelength
α = perpendicular/parallel velocity
I_B = beam current
G = geometric factor (mode dependent)
$\delta v_z/v_z$ = axial velocity spread
Δ = $\omega + |k_z|v_z - \Omega_c$ (frequency mismatch)

The field has the characteristic cosine dependence with finite amplitude at $z = 0$ and zero amplitude at $z = L_c$ implying infinite backward wave gain or oscillation. Once a sufficiently long interaction length has been chosen, a non-linear analysis is required to predict the output power.

NON-LINEAR BEHAVIOR OF THE GYROTRON BWO

A self-consistent simulation model based on the slow time scale orbit equations coupled to Maxwells Equations was modified to be applicable to the BWO problem.(2) The boundary conditions for the electric field correspond to power matched both at the input and output, i.e.,

$$\frac{dE}{dz} = ik_z E \qquad \text{(input)}$$

$$\frac{dE}{dz} = -ik_z E \qquad \text{(output)} .$$

An efficient searching scheme ("star search method") is used to find the unknown field amplitude at the input and the oscillation frequency ω which allows the boundary conditions to be satisfied.

As a first example, the output power as a function of interaction length was determined for a 50 kv 3 amp BWO operating at 100 GHz (30% above cutoff) in the TE_{11} mode. The results are illustrated in Fig. 2. The critical length L_c was found by extrapolating down to zero output power. This was in agreement with linear theory when the frequency mismatch Δ was taken from simulation results. The output efficiency reaches a local maximum of about 10% when the

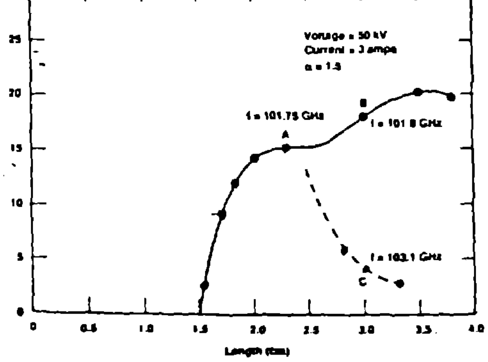

Fig. 2 Satur-te- C-t- -t

length becomes 50% larger than the critical length. The axial mode profile at this length has an approximate cosine dependence as predicted from linear theory (Fig. 3). When the length is further increased, the solutions become double valued with a high and low efficiency branch. Figure 4 shows that the high efficiency branch approximately corresponds to a cosine field dependence while the low efficiency branch corresponds to a field dependence with higher order axial variations.

It is convenient to be able to couple the power out in the forward direction. This can be done by placing a reflecting wall at the input and coupling the reflected power out at the output as in a conventional oscillator. Since the beam interacts only with the backward wave, this is equivalent to coupling the power out at the input.

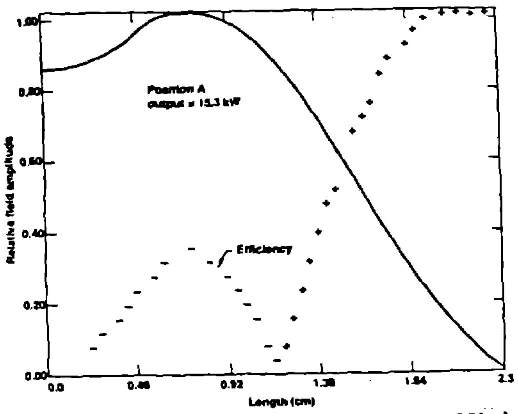

Fig. 3 Relative Field Amplitude and Efficiency vs Length for Solution A of Fig. 2

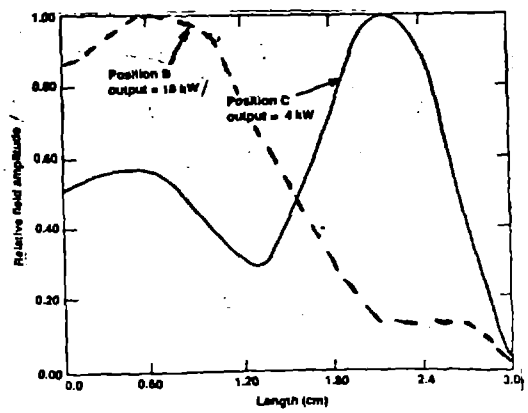

Fig. 4 Relative Field Amplitude vs Length for Multiple Solutions B and C of Fig. 2

DESIGN FOR A 250 GHz 10 kW GYROTRON BWO

Figure 5 is a schematic of a proposed tunable BWO gyrotron operating in the TE_{12} mode at 250 GHZ. A solid beam on axis is generated using the Pierce/wiggler gun configuration This ensures mode control by effectively interacting only with modes which peak on axis (m=1). The interaction length of 14 λ_0 is too short for exciting the TE_{11} mode. Rotational energy is initially imparted to the beam by a resonance between the cyclotron frequency and wiggler frequency ($\propto \sqrt{\text{voltage}}$) in the combined axial/wiggler fields. With a modest change in voltage (60 kv → 70 kv) the wiggler can be driven off resonance greatly reducing the rotational energy. This in turn increases the axial velocity in the circuit thus lowering the output frequency. Electronically tuning the voltage by 16% can change the frequency by 6%. The output power can stay reasonable constant over this range since at the upper frequency the rotation and efficiency is highest but the beam power is lowest while at the lower frequency the rotation and efficiency is lowest but the beam power is highest (space charge limited gun). Table 1 shows the predicted performance of the BWO at the upper and lower ends of the tuning range. These simulations were done using realistic velocity spreads known to occur in Pierce/wiggler systems. They predict power levels over 12 kW with ~10% variation in power over the required tuning range near 250 GHZ.

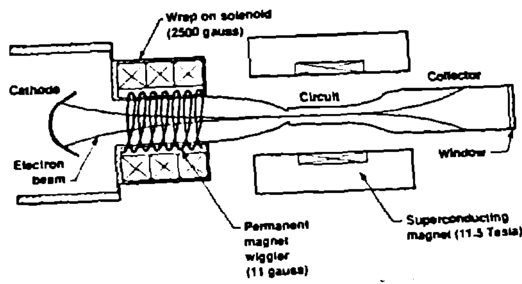

Fig. 5 Schematic of 250 GHz 10 kW Tunable Gyrotron BWO

Table 1 Predicted performance of TE_{12} Gyrotron BWO when electronically tuned over 6% range

Frequency	Voltage	Current	α (wiggler)	α (circuit)	$\Delta V_z/V_z$	$\Delta V_r/V_r$	Power Out
f = 249.6 GHz	70 kV	5 amps	0.0936	0.8181	6%	9%	12 kW
f_1 = 264.8 GHz	60 kV	4 amps	0.1326	2.0	12%	3%	13 kW

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